LENS® and SFF: Enabling Technologies for Optimized Structures

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ABSTRACT

Optimized, lightweight, high-strength structures are needed in many applications from aerospace to automotive. In pursuit of such structures, there have been proposed analytical solutions and some specialized FEA solutions for specific structures such as automobile frames. However, generalized 3D optimization methods have been unavailable for use by most designers. Moreover, in the cases where optimized structural solutions are available, they are often hollow, curving, thin wall structures that cannot be fabricated by conventional manufacturing methods.

Researchers at Sandia National Laboratories and the University of Rhode Island teamed to solve these problems. The team has been pursuing two methods of optimizing models for generalized loading conditions, and also has been investigating the methods needed to fabricate these structures using Laser Engineered Net Shaping™ (LENS®) and other rapid prototyping methods. These solid freeform fabrication (SFF) methods offer the unique ability to make hollow, high aspect ratio features out of many materials. The manufacturing development required for LENS to make these complex structures has included the addition of rotational axes to Sandia's LENS machine bringing the total to 5 controlled axes. The additional axes have required new efforts in process planning. Several of the unique structures that are only now possible through the use of SFF technology are shown as part of the discussion of this exciting new application for SFF.

INTRODUCTION

Optimization techniques offer the promise of lightweight and high strength structures for many applications including aerospace. Though some analytical solutions have existed for almost 100 years, there has been little utilization of optimization due to the difficult, often iterative, math needed for analytical solutions, the extensive computing requirements of finite element solutions, and the lack of a method to create the optimized structures once they are designed. Optimized structures often have an organic look with smooth curves, and many regions that are inaccessible for conventional machining process. Advances in computing power and research into better design methods for optimizing structures, and developments toward fully 3D optimization have brought the design of optimized structures into the realm of usefulness. Concurrently, solid freeform fabrication (SFF) methods such as LENS have presented economically feasible means of creating these structures. This work has developed fully 3D methods of optimization using two independent methods and developed Sandia's LENS manufacturing capability to the point creating fully 3D optimized structures.

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OPTIMIZING STRUCTURES

Outside of a few specific applications such as automobile frame optimization, very few designs are optimized. Instead they rely on the expertise of a human designer. An example is the electronics housing shown in Figure 1. The rib-on-plate on the side of the enclosure was first estimated by an expert designer who chose the angles, cross-sectional geometry, and the intersection radii of the ribs. This design was then analyzed by FEA to determine if the design functioned as required. If not, adjustments were made, but no optimization was done to design these features. If the geometry had been optimized, the result could have been a stronger structure that required less material and allowed the mass to be utilized at another location in the structure where it was needed.

Figure 1. Electronics housing showing non-optimized rib-on-plate structure

Current research into methods of optimization generally fall into two categories: material removal and material redistribution. Material redistribution methods do not require the specialized finite element code and excessive iterations needed by material removal methods. Because of these advantages, the redistribution methods were selected for this work. Advanced Topological Optimization (ATO) [1] is a method in which a final mass for an object is selected. An enclosing geometry is selected as shown in Figure 2(A) and the entire geometry is given a reduced density such that the total mass is the desired final mass. This geometry is meshed and then analyzed using a commercial finite element package. The resulting strain field is then utilized to redistribute the part density. Any node with higher strain is given an increased density while nodes with low strain are given reduced density all while maintaining the same overall part mass. The density differences result in stiffness differences in the part. The part is then analyzed again and the process repeated until conversion criteria are met. Figure 2(B) shows the final optimized result of a center loaded, simply supported beam as results from ATO. This result agrees with analytical models.

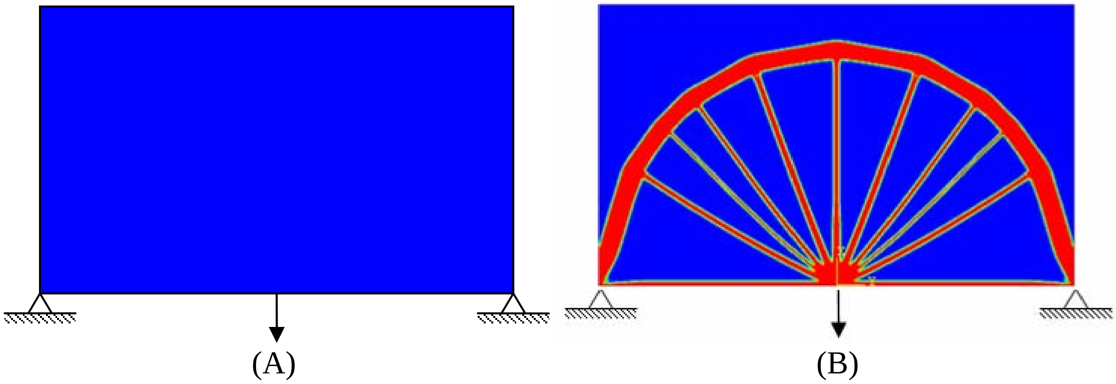

Figure 2. A simply loaded beam subjected to center loading is shown in the non-optimized (A) and optimized(B) topologies

Much of the work of this research has been to extend the optimization methods to fully 3D geometries. This work has required several smaller challenges to be solved as well. Some parts have required the development of exclusion regions for the optimization process. An example of an exclusion region would be a bolt hole on a landing gear. The location of the bolt hole might be determined by the required motion path of the linkage to retract the landing gear. The size of the hole would be determined by the needed strength of the bolt or fastener to connect the landing gear to a strut. This hole would need to be excluded from the optimization so that the geometry and location would remain constant. Another challenge has been the need to export the optimized geometry as a solid model or STL file for the manufacturing process to be able to construct the geometry. After optimization, the edges of the geometry are a continuous grading of density from fully dense to almost zero density, but there isn't a defined edge to the geometry. A marching cube method was utilized to work through the mesh of the optimized geometry and to select which regions would be designated as the part and to export an STL that accurately defined the geometry.

Through this project, a significant effort was undertaken to extend the analytically optimized solution [2] to new 3D geometries so that the ATO optimization results could be checked against analytical solutions. Several optimized geometries are shown in Figure 3 including a center loaded tripod structure and a torsionally rigid loxodrome that exhibits compliance in the bending and axial directions. Additionally a case study of an optical lens housing was utilized in testing as shown in Figure 4. In this case the housing's mass was redistributed to minimize the deflection of the housing under load. The solution cannot be checked analytically, but was instead checked using another optimization method developed by the team based on a strategy developed by Belytschko[3].

(A) (B)

Figure 3. Two structures that were optimized using ATO. The tripod structure (A) has 3 simply supported points and a center loading. The loxodrome (B) has high torsional stiffness, but is designed to have bending and axial compliance.

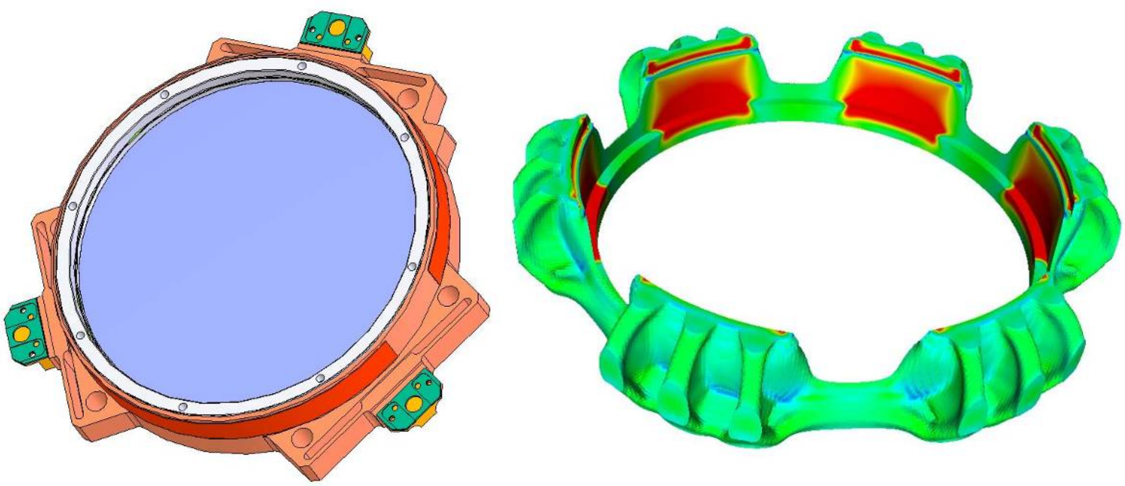

Figure 4. The lens housing (left) deflected under the loading required to secure the optic. The optimized structure (right) redistributes material to minimize deflection in the housing.

LENS® FABRICATION OF OPTIMIZED STRUCTURES

With the development of the optimization methods proceeding nicely, it was necessary to develop the manufacturing processes required to make the optimized topologies. These topologies are ideally suited for SFF methods including LENS. Sandia National Laboratories' LENS machine was a 2-1/2D machine with 3 orthogonal linear axes. The physics of the process limited it to producing parts with a maximum of 45° of overhang, and more realistically 20° of overhang without special process development. Because of the topology of the optimized parts, full 3D capability was needed for the LENS system. This was achieved by the addition of azimuth and elevation rotary axes as shown in Figure 5. Other groups have achieved this capability using robotic arms or rotary laser wrists, but the AZ-EL solution gave the maximum amount of motion in Sandia's machine at the most reasonable cost.

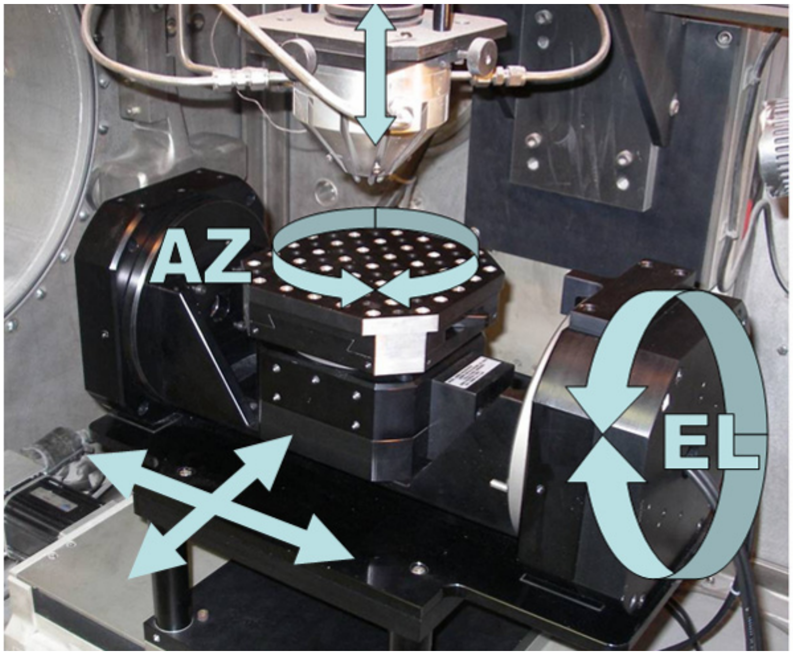

Figure 5. Rotary axes for elevation and azimuth were added to the 3 existing linear axes in the LENS machine.

Though these axes add the motion capability needed to create fully 3D parts, the process planning required to utilize these axes is significantly more difficult than for the 2-1/2D case. Because of the need to quickly achieve a process planning solution for this work, the team chose an approach that takes advantage of the typical topology of optimized structures, but does not solve the generalized 3D process planning problem. The simplified solution was possible because many of the optimized structures consisted of multiple "legs" that are essentially straight and curved sections that are roughly cylindrical. A process planning strategy was developed in which each of these fingers would have a medial axis spline created along the length of the finger. Points would be located along this axis at an interval matching the desired layer thickness. At each point, a plane would be created perpendicular to the medial axis and the intersection curve produced by that plane and the geometry of the finger would give the area to be built by the LENS process.

Further research into the creation of medial axes by methods such as medial axis transformation, skeletonization, and thinning showed this technique to be powerful, but also to have a number of significant challenges (smoothing, sensitivity to surface roughness, etc.) Because of the short timeframe of the project, it was decided that an alternative approach was needed. While it is difficult for computers to recognize topology, it is something that humans are quite adept at doing. So the decision was made to utilize the human capability by having the user trace a spline up the exterior of each finger using a solid modeling package (SolidWorks, in this implementation, though any 3D package could be utilized for this task). An example of splines sketched on an optimized part is shown in Figure 6. Once the spline is drawn, a macro written using SolidWork's application programming interface (API) puts points along the spline at the desired interval, creates a perpendicular plane at each point, and then determines the intersection curve of that plane and the geometry adjacent to the point (see Figure 7). A point set for the curve and the plane's normal vector are exported to a file. These points and vectors are then used by a C program to create the M&G codes used to drive the LENS machine.

The new set of axes in the LENS machine was mathematically modeled using a set of kinematic transformation matrices. The inverse kinematics of the machine were then determined and put into the controller so that a point and normal vector could be designated in part space and the machine would determine the means of moving the axes to get to that point. A simple part constructed using this methodology is shown in Figure 8.

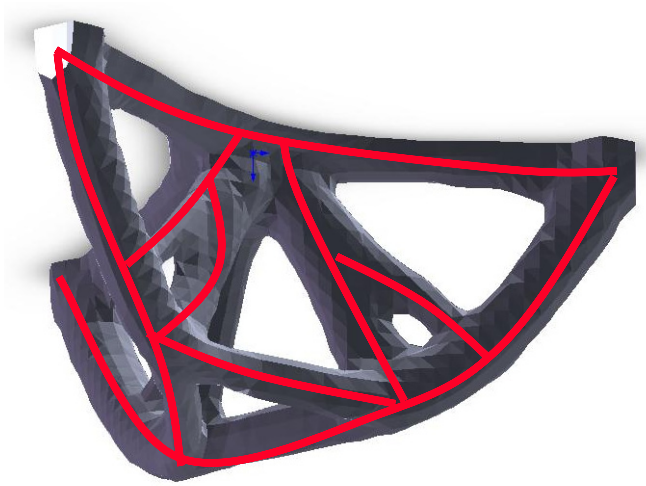

Figure 6. The optimized tripod is shown with splines drawn along the legs of the structure.

(A) (B)

Figure 7. For process planning, a spline is drawn along the surface of a part (A) and then planes normal to the spline are constructed(B). The intersection of these planes and the geometry gives a bounding curve used for path planning.

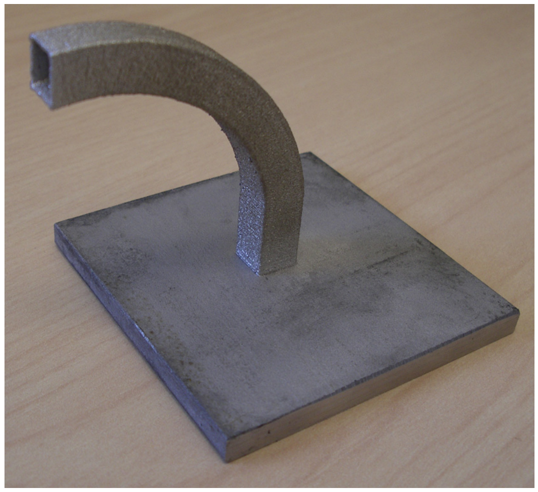

Figure 8. LENS part created using process planning methods developed for this project.

CONCLUSIONS

Robust 3D topological optimization routines will enable designers to design optimal structures for many applications. New topological optimization capabilities were developed and tested against newly derived 3D analytical optimization models in addition to models created by other optimization methods. There had previously been no means of making many of these optimized structures, but LENS and SFF methods hold the key to creating many of the structures in functional materials. Process planning was developed to make the fabrication of these structures possible and Sandia's LENS machine was upgraded to become fully 3D. The project has shown this exciting application of LENS and SFF to have great potential as a useful tool for design engineers.

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